Comment on "Spatial line nodes and fractional vortex pairs in the Fulde-Ferrell-Larkin-Ovchinnikov phase":

Recent observations [1, 2] of a high field superconducting (SC) phase in $CeCoIn_5$ have led to intense interest [3, 4] in modulated *vortex* phases induced by the paramagnetic depairing. Authors of Ref.[5] have discussed a possibility that, as a candidate of the high field state in $CeCoIn_5$, a crisscrossing lattice of *integer* vortices with a fractional magnetic flux replaces the so-called LO vortex lattice [4, 6] with periodic nodal planes perpendicular to the field **H** and have argued that thermal conductivity κ's data [7] are consistent with the former state rather than the latter. Below, it is pointed out that available experimental facts in $CeCoIn_5$ are incompatible with properties peculiar to the former state and that the analysis in Ref.[5] is lacking in a firm theoretical basis.

First, based on their notation [5], the state they propose is more stable than the ordinary LO vortex lattice [4, 6] if $2\tilde{\beta}_1\beta_A(0)/\beta_A(\tau) > 2\tilde{\beta}_1 + \tilde{\beta}_2 > 0$. When $\eta_1 = \eta_2$, this condition implies assuming the case with a second order $H_{c2}(T)$-transition. Opposite to this, the H_{c2}-transition in $CeCoIn_5$ at lower temperatures is discontinuous [1, 2], implying that, according to their criterion, the LO vortex state is stable as the high field phase. In fact, the structure of their phase [5] is described by a couple of order parameters, q and τ, defining differences in structures from the Abrikosov lattice with $q = \tau = 0$, and thus, the structural change between the crisscrossing and Abrikosov lattices needs to occur through a couple of transitions or a single discontinuous one in contrast to a single continuous transition in $CeCoIn_5$ [1, 2, 7, 8]. Besides this, they have assumed the validity of the perturbative expansion in the gradient *perpendicular* to **H** in their starting model. This gradient expansion is valid only in the case with a large enough Maki parameter [6] where the $H_{c2}(T)$ and the vortex state at lower temperatures are described in the ballistic (or clean) limit by the SC order parameter in not the lowest Landau level (LL), assumed in Ref.[5], but a higher LL [3]. In the next lowest LL state, periodic nodal lines appear with a distance of the order $(\sqrt{2eH})^{-1}$ in the plane perpendicular to **H**, and hence, the transition between such a higher LL state and the ordinary Abrikosov lattice is inevitably of first order in contrast to the observation in $CeCoIn_5$. We note that, according to Fig.7 of Ref.[3], a modulation parallel to **H** does *not* occur in the higher LL.

One of key experiments reflecting the structure of the high field state is the ultrasound measurement [2], in which the sound velocity has remarkably decreased upon entering the high field phase from the Abrikosov state only in the Lorentz mode with a displacement perpendicular to **H**. This has been explained [4] as an evidence of the presence of nodal planes perpendicular to **H**. On the other hand, the crisscrossing lattice represented in the lowest LL [5] has no nodal planes, and the vortices, which are not parallel to **H**, will be strongly pinned by the *crystal* lattice even in the non-Lorentz mode. Thus, this state realized as the high field state would result in an enhancement of sound velocity in contrast to the observation [2]. Further, the fact [8] that the discontinuous H_{c2}-transition and the high field phase appear over *wider* temperature ranges at a *higher* pressure implies that a magnetic ordering is inessential to them. Finally, the observed feature [7] noted in Ref.[5] that κ parallel to **H** is greater than that perpendicular to **H** is also seen clearly in the Abrikosov state in lower fields, and thus, no one can regard it as a feature peculiar to the high field phase. The increase of κ parallel to **H** in the high field phase originates from a decrease of the amplitude of SC order parameter [4] and does not contradict the picture that the high field phase is the LO vortex lattice with nodal planes perpendicular to **H** [9].

In conclusion, the high field phase of $CeCoIn_5$ is not the crisscrossing lattice [5], although the proposed state might appear in future in other materials.

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